Air Muscle Actuated Low Cost Humanoid Hand

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Abstract: *The control of humanoid robot hands has historically been expensive due to the cost of precision actuators. This paper presents the design and implementation of a low-cost air muscle actuated humanoid hand developed at Curtin University of Technology. This hand offers 10 individually controllable degrees of freedom ranging from the elbow to the fingers, with overall control handled through a computer GUI. The hand is actuated through 20 McKibben-style air muscles, each supplied by a pneumatic pressure-balancing valve that allows for proportional control to be achieved with simple and inexpensive components. The hand was successfully able to perform a number of human-equivalent tasks, such as grasping and relocating objects.*
Keywords: *McKibben air-muscle, pressure balancing valve, low cost, humanoid hand, robotic arm*

1. Introduction

Much work over the recent years have been involved in the creation of a humanoid hand, where degrees of freedom and size of the hand and forearm are designed to be as close as possible to human proportions. Over time various hands were built from a simple 3 finger system without a thumb (Okada, 1982), all the way to an almost exact replication of a human hand (Shadow, 2005), comprising of 4 multi-jointed fingers and a thumb. Several forms of actuation have been utilised in these hands such as electrical revolute motors (Okada, 1982; Salisbury & Roth, 1982), DC motors (Bekey et al., 1990), pneumatic actuators (Jacobsen, 1986) and pneumatic muscles (Lee & Shimoyama, 1999; Shadow, 2005). The most advanced hand created to date is the Shadow Hand, comprising of 25 individual degrees of freedom, actuated entirely by compliant air muscles (Shadow, 2005).
The objective of this work was to design and computer control a pneumatic air muscle actuated robotic hand, incorporating basic human finger, thumb, forearm and elbow movements. The hand was built to human adult male size proportions. The first design goal of the hand and arm was to pick up an object such as a soft drink or small water bottle. This task was to be performed in a similar manner as a human would perform the task. The hand is then to transpose the can to another position on the arms radius, as specified by the user. If the hand could sufficiently perform this task, then it would be possible to program it to perform many others within its degree of freedom limitations. The hand was to perform this task at a pressure of between 2 to 3 Bar, and all movement was to be controlled via simultaneous PID algorithms written into the driving software. The software was written to run on a PC with an 8255 interface board. Also, the hand was to be constructed using low-cost yet effective components.

2. System Overview

The entire physical system is illustrated in Fig. 1. The physical hand and arm comprises 4 fingers, a thumb and elbow, all actuated via air muscles. Each air muscle requires a precisely controlled source of air pressure to accurately position the stroke-length of each air muscle, positioning the hand fingers and forearm in the required positions. This controlled source of air is supplied by the Valve Board.

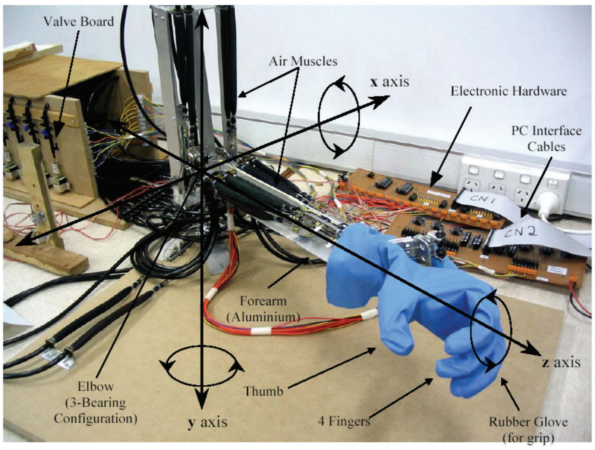

Fig. 1. Physical Component Overview Diagram

The Valve Board uses 20 valves to convert a single raw compressed air supply of approximately 2.5 Bar to 20 controlled pressure lines. Each valve is fully proportional,

and is electronically controlled to regulate the pressure required in each air muscle. The electronic control signals are provided from the Electronic Hardware. The Electronic Hardware consists of an input card and an output card. The output card filters, buffers and amplifies PWM signals from a PC and sends the final signals to the valve board. The input card accepts the analog feedback position signals from the Hand, and converts them into a digital signal suitable to interface to the PC. The PC, via a digital 8255 Input/Output Data Acquisition card, interfaces the Electronic Hardware with the PC. Purpose-written software controls the system via PID algorithms. The PC also interfaces the system to the user via a custom designed GUI, displaying system responses and allowing the user to input new set points, PID gains, etc.
The interactions of the sub-systems are illustrated in the block diagram, Fig. 2.

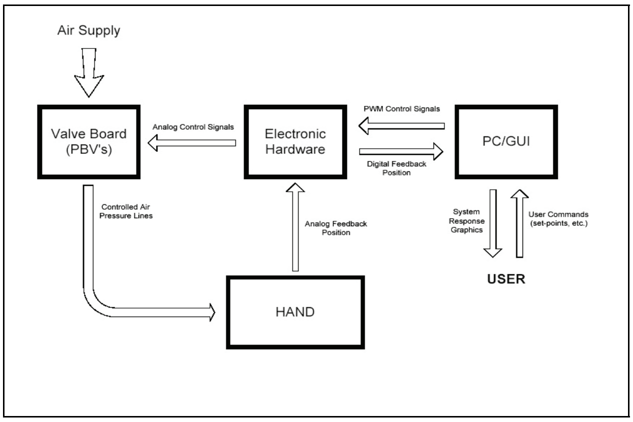

Fig. 2. Entire System Overview Block Diagram

3. The Hand and Air Muscle Design

The hand is comprised of three main subsections, represented as a block diagram in Fig. 3. These include the air muscles, the mechanical joints (fingers and elbow) and the feedback potentiometers. All sections are contained directly in the forearm (apart from those relating to elbow movement).

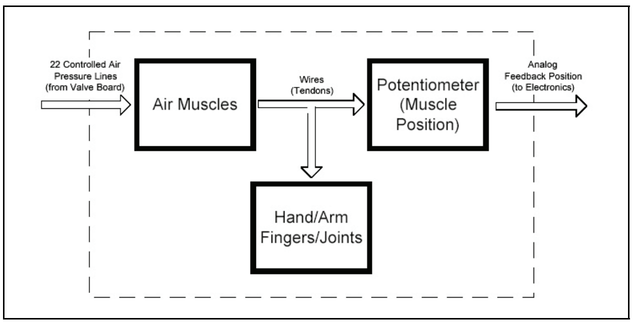

Fig. 3. Hand System Block Diagram

Complete actuation of the hand is obtained solely via the use of air muscles. No electric means of actuation has been used to provide any movement to the hand and elbow. The 20 controlled air lines from the Valve Board connect directly to the 20 individual air muscles on the hand and arm. Each joint is connected to two air muscles in a complimentary configuration (retraction and contraction). When air pressure is supplied to an air muscle, it contracts by up to 25%, this providing the contraction or retraction of each joint. Controlling the air pressure in an air muscle directly controls the force an air muscle can provide, providing control over the joint position.
Each air muscle is connected to a joint or finger via wires, similar to the tendons in a human arm. The hand comprises 4 fingers with one degree of freedom each, a thumb with 3 degrees of freedom, and an elbow with 3 degrees of freedom. Each finger comprises 3 joints and each joint moves together simultaneously, contracting and retracting by the same angular measure. Each joint and finger comprises two air muscles in a contract-retract configuration, providing force control in both directions.
Each degree of freedom is physically connected directlyto a potentiometer. Depending on the displacement the joint actuated by the connected pair of air muscles, the potentiometer position changes, providing a corresponding analog voltage signal between 0 to 5V DC to the Electronic Hardware.

3.1 Air Muscles
The choice of actuator for this work was the air muscle, also known as the McKibben Pneumatic Artificial muscle or a Rubbertuator (Iovine, 2000). It was developed in the area of artificial limb research in the 1950's and 1960's ((Gavrilovic & Maric, 1969) cited in (Chou & Hannaford, 1996)) and patented by R.H. Gaylord and applied to orthotic appliances by J.L.McKibben ((Gaylord, 1958) cited in (Klute et al., 2002)). Like a biological muscle, a McKibben air muscle contracts when activated, and experimental evidence demonstrates that the device has force-length properties similar to biological muscle (Klute et al., 2002). This allows researchers to attach air muscles to a robotic skeleton at primary biological muscle locations, making it often the preferred choice of actuator in the study of biomechanics (Iovine, 2000). Other properties that make the McKibben air muscle popular in the biomechanic field include their softness and lightness (Iovine, 2000). They are also compliant with a high power to weight ratio (400:1), can be twisted axially, used on unaligned mountings and provide a contracting force around bends.
The McKibben air muscle is a simple actuator to manufacture. A long-bladder balloon such as those supplied from party shops, is suitable for use as the muscle's inner bladder (Masclet, 2003). Polyester braided sheathing of various diameters, depending on the size of the air muscle required, is available from many electronic distributors (Iovine, 2000). Both these main components are inexpensive and readily available. This allows a low-cost air actuator to be built, as shown in Fig. 4.

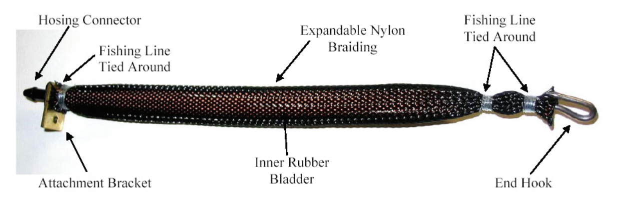

Fig. 4. Air Muscle Component Break-up

Each custom built air muscle cost approximately AU$2.00 to manufacture, made from the following components:

1 x Inner Rubber Bladder (long party balloon)
1 x Expandable Braided Sheath (cabling accessory, ∅10mm nominal, ∅6mm min, ∅18mm max)
1 x End Hook (nail bent into a hook shape)
1 x Attachment Bracket (custom cut and drilled brass plate)
1 x Pneumatic Hosing Connector (Reticulation hose joiner)
1 x Nylon Fishing Line (∅0.27mm, 3 x ~30cm lengths)

Assembly of the above components was as follows. The inner bladder was firstly inserted into the expandable braided sheath. The right end was then tied with fishing wire to create a seal. A nail (flat side) was then inserted into the same end, and another piece of fishing wire tied around the braiding to lock in the end of the nail. The remaining section of the nail was then bent into a hook shape.
A reticulation hose joiner was then inserted into the left end of the rubber bladder, with the bracket (designed for easy connection onto the forearm) between the bladder and the joiner. The end was then tied with another piece of fishing wire, sealing that end and locking in the bracket. This completes the manufacturing of a single air muscle. This process was used to make all 20 air muscles required for full actuation of the hand and arm.

4. Valve Board System Design

The Valve Board (represented as a block diagram in Fig. 5) main function is to interface the electronics with the compressed air-supply to supply 20 individually controlled air pressure and flow rates needed to control the 20 air muscles in the hand.

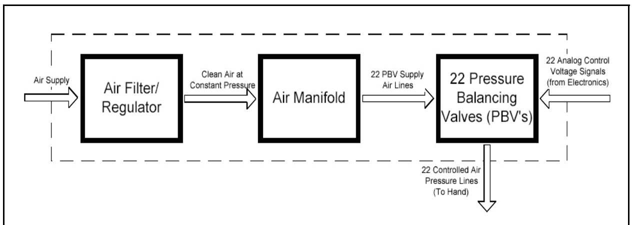

Fig. 5 - Valve Board System Block Diagram

Air is supplied to the system via an air supply with pressure continually above 3 bar. This air, to provide system stability over continuous usage, first needs to be filtered to remove oil and water. The air is then regulated to maintain overall system pressure at approximately 2.5 Bar, a sufficient pressure to provide full functionality to the mechanical system whilst preventing the pneumatic system from experiencing undue stress.
The filtered and regulated air then enters a large air manifold. The manifold is needed to provide continuous and consistent flow rates to each of the 20 air valve supply lines connected directly to the manifold. The air valves designed have been named Pressure Balancing Valves (PBV) due to the way they operate, which is explained in the following section. The entire physical Valve Board is presented in Fig. 6a.

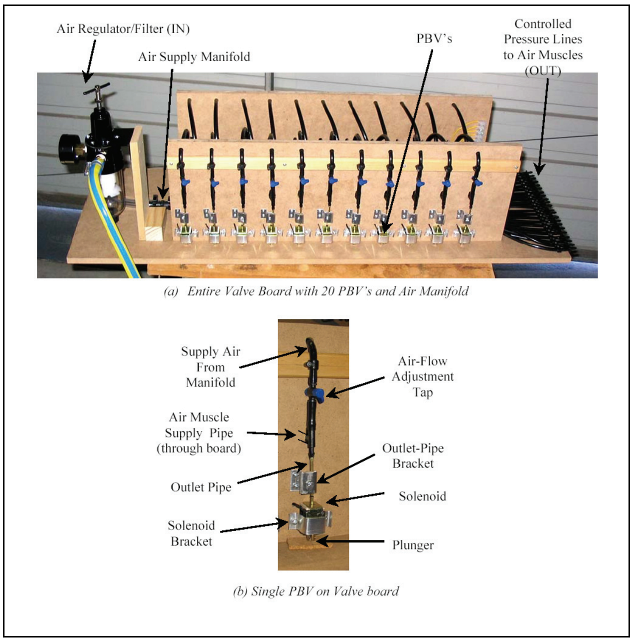

Fig. 6. Valve Board (a) and PBV (b)

Custom designed and built, each PBV (Fig. 6b), accepts an analog control voltage between 0 to 9V from the Electronic Hardware. This voltage signal directly controls the flow rate proportionally through the PBV, in turn controlling the pressure in the corresponding air muscle supply line. Each PBV cost approximately AU$15 to build.

4.1. PBV Design
To move an air muscle to a required position between its minimum and maximum contractions, the air pressure inside the air muscle must be controlled. To control the position of an air muscle with standard pressure regulating valves is a heavy and slow choice. (Van Ham et al., 2003) The preferred choice thus far has been to use fast switching On-Off valves, for the reason that fast and accurate pressure control is required (Van Ham & Daerden, 2003). Such work involving accurate real-time position control in robot systems with the use of air muscles, has been undertaken by the Shadow Robot Company and also by the Department of Mechanical

Engineering at the Vrije University in Belgium. Both teams have utilised the same valve choice for their air muscle control. These valves are the Matrix 821NC 2/2 solenoid pneumatic valves. With their reported opening times of about 1ms, flow rate of 180Nl/min and total mass of only 25g, they are about the fastest switching valves currently available (Van Ham et al., 2003).

Other experimental work undertaken in the position control of air muscles where position accuracy is not critically important, have used valves such as the 2/2 Isonic solenoid valve from Mead Fluid Dynamics (Iovine, 2000). Applications mainly involve using the muscle as either hard-on or hard-off. These on-off valves have a maximum operating frequency of 20Hz, compared to the maximum operating frequency of 500Hz with the Matrix valves, making the Matrix valves more attractive for accurate pressure control.

Current commercially available pneumatic valves, either proportional or on-off types, both exceeded the cost limitations for this work. (Matrix 821NC 2/2 quote (Matrix, 2004).) Therefore a custom made valve was designed and created specifically for this work. This particular idea, the PBV, was developed and tested, and due to the attractive results obtained (see Fig. 15) was implemented as the method used for air muscle position control. This idea requires the use of only one PBV to control an air muscle, as opposed to the conventional method of using two on-off pneumatic valves.

Using a PBV to control the pressure in an air muscle, the following setup was implemented. (See Fig. 7.) Air enters a tee, where one branch of the tee connects to the air muscle and the other branch of the tee connects to a PBV.

The air flow rate into PBV is controlled and set with the 'Air Flow Adjustment Tap'. Controlling the amount of air that is allowed to flow out of the system directly controls the pressure in the outlet pipe. A low flow rate out of the system means a high pressure in the outlet pipe, since more air is entering the tee than exiting. Conversely, a high flow rate out of the system means low pressure in the outlet pipe. Since the outlet pipe is directly connected to the air muscle supply pipe via the tee, the pressures in both the outlet and air muscle supply pipes must be equal. This way, the air muscle pressure can be directly controlled.

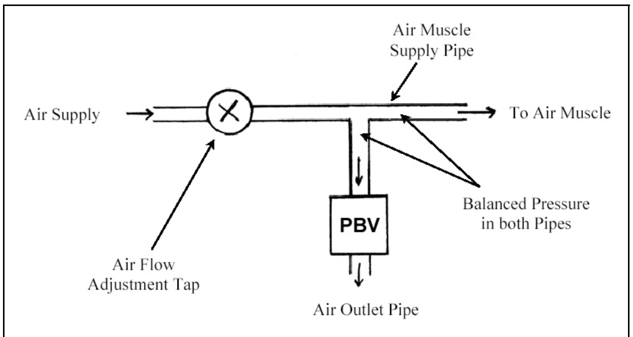

Fig. 7. Air-Muscle/PBV Air Supply Setup

Proportional control of the flow rate out of the system hence controls the pressure in the air muscle, producing the force required from the air muscle. This controlled air flow rate out of the PBV was obtained via use of a modified solenoid. (See Fig. 8) Positioning the solenoid vertically and upside down (plunger on the bottom) allowed gravity to provide a constant force on the plunger in the opposite direction of the electromagnetic force. This enabled the air-gap distance to be directly controlled by applying different currents through the solenoid coil. The pressure of the air flowing out of the outlet pipe also provides a force in the opposite direction to the force provided by the solenoid.

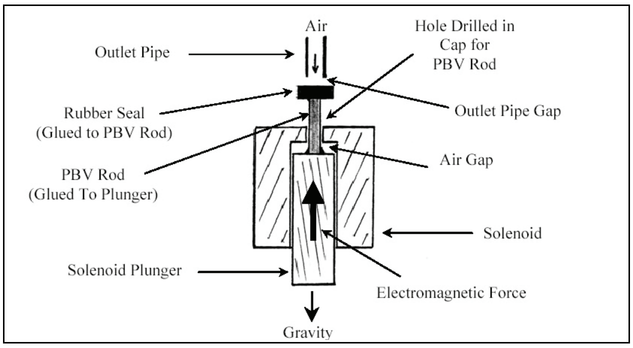

Fig. 8. Modified Solenoid for PBV Usage

By controlling the solenoid's air-gap distance and attaching a rod with a rubber seal to the top of the plunger, direct control over the air flow rate out of the PBV was possible. Balancing the two opposing forces (air flow pressure and gravity verses electromagnetic solenoid force) produces an 'outlet pipe gap' of corresponding length. Proportional voltage control to the solenoid produces this balancing force and thus controls the PBV's outlet pipe air flow rate which in turn controls the air pressure in the air muscle.

Complete pressure control of each air muscle used in the hand was controlled solely via this custom designed PBV method. Each PBV provides fully proportional air pressure control to the attached air muscle directly corresponding to the current through the solenoid coil. Since the solenoid plunger is 'floating', the lack of friction makes this valve accurate for controlling fine pressure increments. For example, each step of a feedback resolution of 255 steps was obtainable with this PBV method. Each PBV was connected directly to the custom designed electronic hardware to provide the required proportional control voltages.

5. Electronic Hardware System

Custom designed and built electronic hardware, represented as a block diagram in Fig. 9, was used to interface the PC via an 8255 digital I/O card to the PBV's. The digital inputs and outputs from the 8255 card are TTL (0 - 5V / Off – On, respectively), with the outputs

providing limited current. This means conversion to and from external non-compatible signals is required.

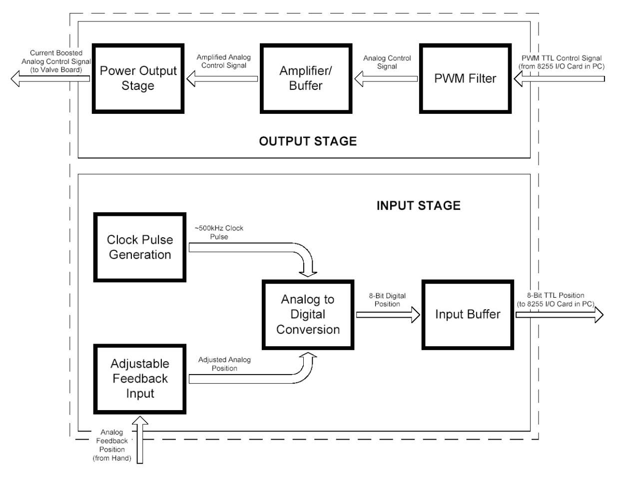

Fig. 9. Electronic Hardware System Block Diagram

The PWM generated signals from the 8255 Card are not suitable for connection to the systems' valves, as they require an analog voltage signal. Thus, the first stage that the raw TTL PWM signals must go through is a filter. This produces an analog voltage, respective to the duty-cycle of the PWM signal. This signal then needs amplification and buffering. Amplification is needed to produce the required valve maximum input voltage limit while buffering is needed to provide suitable current gain to the signal. The final stage is the Power Output stage, where additional current gain is provided to the signal, at a level suitable to adequately control the air valves on the Valve Board.

The input signals returned from the Hand are analog voltages, with magnitude directly corresponding to air muscle contraction via a potentiometer. This analog voltage needs to be converted to a digital TTL signal suitable to interface to the 8255 I/O card in the PC. The first stage the analog signal passes through adjusts the feedback range of the potentiometer on the hand, maximizing available resolution regardless of the full contraction length of the particular air muscle. The adjusted analog feedback voltage is then converted to a digital 8-bit word, allowing the maximum resolution of the position potentiometer on the Hand to have 255 steps. A separate 555-timer circuit provides the necessary clock pulse to the ADC. The converted 8-bit represented position then undergoes buffering before connection to the 8255 I/O card in the PC.

5.1. Single Channel PWM to Analog PBV Control

The PBV's require an input analog voltage between 0 to 9V at 200mA to accurately control the air pressure in the attached air muscle. A low-cost yet effective method to do this was to pulse one TTL output channel from the 8255 Card in the PC, followed by circuitry to filter out the harmonic components of the PWM waveform, leaving only the DC component.

To eliminate harmonic components contained in a particular waveform, a brick-wall filter would be most desirable. These however are expensive and very difficult to build (Palacherla, 1997). A simple yet effect approach however, is to use a simple 2nd order passive R-C low-pass filter, designed to filter out the high frequency harmonic components of the PWM signal. The result of such filtering allows only the DC component of the waveform to be transmitted through the filter. In this way, an analog voltage directly corresponding to the duty cycle of the PWM signal is produced.

Fig. 10 shows the simulated effect that the low-pass second order filter had on a PWM signal (0-10V) with a 50% duty cycle in the time domain at 100Hz. In Fig. 10 the ripple of the filtered waveform has peaks at 5.146V and at 4.853V, giving a maximum variation of approximately 0.3V. This corresponds closely to the physical measured value of 0.32V peak-peak. The PBV did not noticeably react to the 0.3V ripple, the result being a steadily positioned air muscle as required.

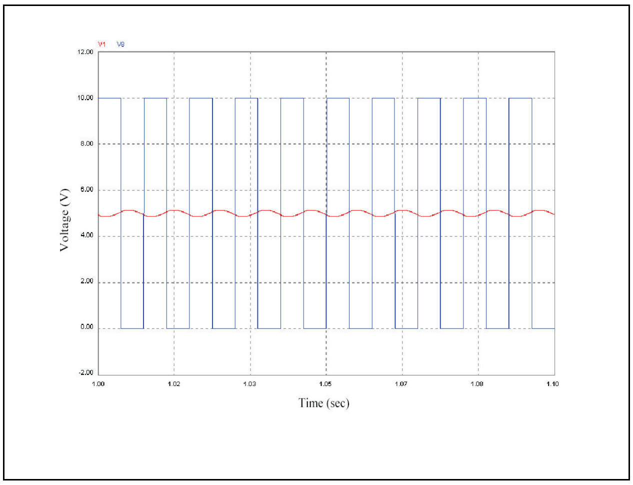

Fig. 10. PWM simulation before/after filtering (100Hz)

Note: The simulation graph is shown using a PWM duty cycle of 50%, as this gives the maximum ripple at the output of the filter due to the maximum ON/OFF time periods produced corresponding to the charge/discharge time of the filter capacitors. In addition, the time scale of the graph starts from time equal to 1 second. This is to omit the transient response of the filter due to the initial charging of the capacitors seen if started from time equal to 0 seconds.

6. PC/GUI System

The control heart of the overall system is the PC and Graphical User Interface (GUI), represented as a block diagram in Fig. 11. This is the means by which the entire

system is controlled, and how control parameters based on the system's response can be implemented by the user.

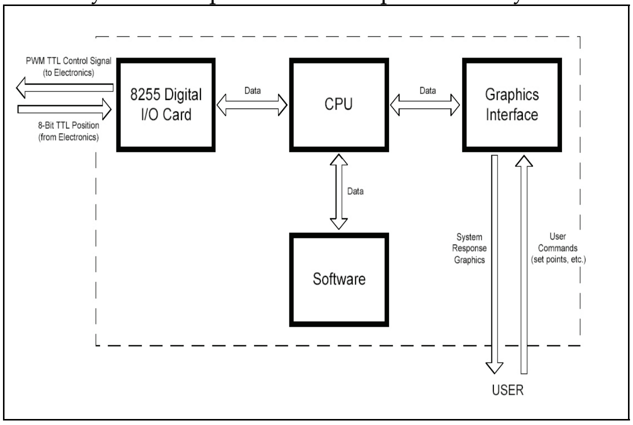

Fig. 11. PC/GUI System Block Diagram

Total control of the system is obtained via the software using PID control algorithms, compiled and run on a 233MHz Pentium PC. The software contains all control algorithms for the Hand's movement and allows the user to interface with the Hand simply and easily by means of a GUI. At the low level, the software written GUI allows the user to adjust control parameters of the system (such as PID gains) to any of the Hand's joints and to see the position response. Higher level GUI usability allows the user to select individual or concurrent finger/elbow joint movements of the hand or to run a predefined sequential task program (such as picking up a bottle of water).
Attached to the PC internally is a Data Acquisition 8255 Digital Input/Output Card. This card allows 48 separate digital TTL bits to be connected to the external electronic hardware. The card is configured so that 24 of the digital TTL bits are Inputs and the other 24 are Outputs. In this configuration, 20 of the digital output bits are used to control each of the 20 air muscles contained in the mechanical hand system via PWM. Similarly, 16 digital inputs are used to obtain the feedback response position for the 10 degrees of freedom. (Configured as two 8 channel, 8-bit ADC's in parallel.)

7. Overall Performance

The primary objective was to create a robotic hand to closely mimic a human hand in size and to perform simple manipulation tasks. Mechanically, the major aspects dealing with the design of the air muscles, elbow, fingers, thumb, forearm, etc. proved successful in accomplishing the task of picking up an object of similar shape to a can of soft-drink. Due to the lack of feedback resolution used throughout the elbow joint however, a can of soft-drink proved to be too short to position the hand accurately to grasp the can consistently. The width of the palm of the hand is similar in height to the soft-drink can. Thus if the hand was not lowered far enough, the thumb and index finger would grasp only air and not the can. Substituting a water bottle for the soft-drink can eliminated this problem. Both objects are of similar diameter, however the water bottle is longer than the soft-drink can by about half. The extra length allowed the thumb to grasp around the object, producing consistent results. Fig. 12 shows the hand holding up a half-filled water bottle.

Fig. 12. Hand Manipulating a Water Bottle

Smooth mechanical movements were obtained from all joints at a level high enough to pick up an object in a predefined position. The only addition made was the addition of a rubber glove inserted over the hand to improve the hands 'grip'. Trialed first without a rubber glove, the grasped object repeatedly slipped out of the hand. With the addition of the rubber glove, this slip was no longer a problem.
The hand was also programmed to mimic certain human hand positions such as giving a 'thumbs-up' after completing a preset control sequence (such as transposing a bottle) or making a fist and shaking it if the bottle were dropped. These positions can be seen with direct comparison to a human hand in Fig. 13 and Fig. 14.

Fig. 13 – Mimicking 'Thumbs-up' Position

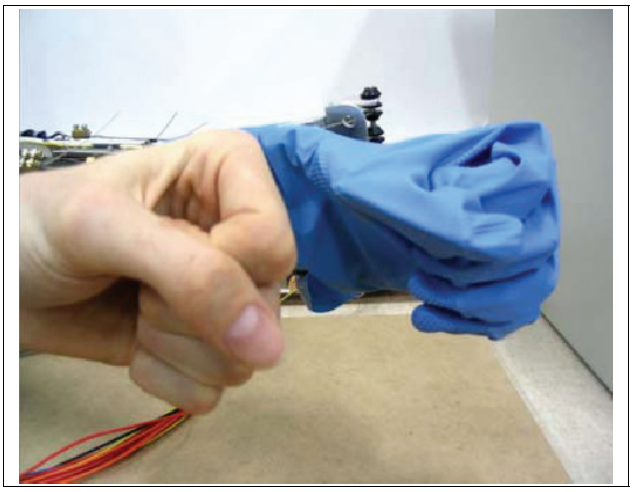

Fig. 14. Hand Mimicking Fist Position

PWM to PBV to Air Muscle Position Control
The total feedback system, encompassing the PWM to analog filtering, PBV response from the control signals, and the potentiometer A/D 8-bit feedback, all running under PID control, provided a simple low-cost yet effective means of control over the contraction percentage of each air muscle. A simple test rig was setup with an air muscle, potentiometer and PBV under PID control, and a typical response obtainable is shown in Fig. 15. The target input was a 180 bit step (approximately 3cm air muscle stroke length), sent at approximately 3.5 seconds.

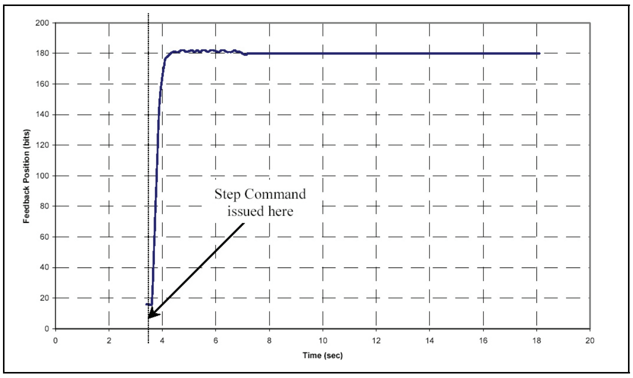

Fig. 15. Tuned Response of a Single Air Muscle (at 2.5Bar supply pressure)

Fig. 15 shows a tuned PID control response with minor overshoot, actuating to the set-point of 180 bits (out of 255) in less than 1 second. Considering the methods used and the custom designed PBV's used to control the air pressure in each air muscle, the results proved more than adequate in providing a suitable method for actuating the entire hand-arm mechanical system.

8. Conclusion

Overall, the design of the entire system proved successful in building an air muscle actuated humanoid hand to accomplish the task of picking up a small water bottle. Mechanically the hand performed to a level satisfactory to manipulate simple objects in the manner in which a human hand would. The subsystems designed to accomplish this task also proved satisfactory in terms of overall accuracy and response speed. While problems were encountered however, they proved small enough in the overall scope of work performed not to hinder the creation and performance of the hand.
The primary goal of the work was to design, build and computer control a pneumatic air-muscle actuated robotic hand. It was to incorporate basic human finger, thumb, forearm and elbow movements, and was to be built to human sized proportions. This goal has been accomplished. The additional goals included picking up a full can of soft-drink, grasping the can in a human like manner, and transposing the can to another position. While a soft-drink can proved to be slightly too short to be used, the hand had no problems with manipulating an object of similar diameter but slightly longer, such as a water bottle.
Reliability of the hand proved accurate to pick up an object as planned once PID tuning was completed, at a 'gentle' speed. This goal was demonstrably met, as once programmed the hand would repeatedly pick up the object in the set position without noticeable failure (dropping the object, etc). PID control was also accomplished, able to control all 20 air muscles at once, with a GUI interface. All actuation was also accomplished at a pressure between 2 and 3 Bar as desired.
Additional goals also achieved include picking up an empty can of soft-drink, and picking up a tennis ball. Picking up a ball by itself was not possible due to the lack of feedback accuracy, however the hand was able to grasp a ball firmly if the user placed the ball firstly in the hand's palm. GUI goals such as the ability to control each finger individually or collectively was also achieved. (This level of control was needed to assist in preliminary testing anyway, and was designed before set Control Path Sequences were created.) A simple demonstration sequence was also created to move the hand's fingers in a natural way, at a gentle speed. Movies of the hand in action are available from http://mech-eng.curtin.edu.au/lindsay/pneumatichand/.

Finally, designing the entire system with a 'low-cost' approach in mind, enabled the entire system (excluding the PC and air compressor) to be built for less than AU$1500.

9. Future Work

Future work ideas include the development of this work into an arm and hand that is able to perform at a higher level of reliability, and incorporates a functional wrist. A method of reducing static friction between the tendons and the joints is another area that would greatly enhance the speed and accuracy control movements of the hand.

While this arm was able to perform simple manipulation tasks and provide simultaneous joint movement of each of its 10 degrees of freedom, increasing the feedback resolution would enable a higher degree of positioning accuracy to be obtained. This would enable the hand to provide a finer accuracy level, in turn permitting the manipulation of smaller and more delicate objects.

Operating the hand at a higher pressure than the 2.5 Bar used would increase the output power of the hand (grip strength and speed of response) while causing no change in arm size. New considerations however would have to be given to the tendons used and an increase in static friction between the tendons and joints.

Implementing the above enhancement ideas together with the creation of a moveable elbow (requiring the creation of a shoulder) would enable the hand's manipulation area to enhance dramatically, though would require a significant design overhaul of the entire elbow system.

Further work that will directly follow on from this prototype involves designing a complex air muscle actuated hand with increased dexterity and sensoring abilities. Such a hand can be used to communicate to a deaf-blind person, where touch is the persons only sense of communication to the outside world. Advanced control methods over PID can be then implemented to teach the hand how to communicate and receive information from the user. This way a system can be created, where a lay person, through the means of such an intelligent biomechanical system, can communicate (transmit and receive) with a deaf-blind person. This concept offers substantial significant opportunities for future human-computer interactions.

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